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2 Case studies of high-rise buildings

In the previous chapter, tall buildings in their current form of design were criticised for their contribution on the intensification of the urban heat island (UHI) effect. It was hypothesized that poor architectural design – either due to the lack of knowledge by architects or the existing traditional commercial attitudes by developers – is a major factor in making tall buildings intense energy consumers; hence further investigation should be carried out. As the starting-point of this research, this chapter aims to distinguish the main design principles that are incorporated in sustainable and conventional high-rises. In this regard, a comparative study between nine sustainable and three conventional high-rise office buildings in three climate groups (temperate, sub-tropical & tropical) concerning their energy performance and the use of architectural design strategies is conducted. For each category of climates, the effectiveness of different design strategies for reducing the cooling, heating, ventilation and electric lighting energy demands are analysed (in sections 2.3-2.5). Lessons from these buildings (both general and climate specific) are defined in section 2.6. Afterwards, the energy use intensity (EUI) of twelve case studies is compared to related energy benchmarks in each climate/context. In Section 2.8, the mean monthly outdoor air temperature of each case is compared to comfort temperatures based on adaptive thermal comfort (ATC) models versus predicted mean vote (PMV) models. Finally, a general discussion of findings is provided in section 2.9.

A comparative study: Design strategies for energy-efficiency of high-rise office buildings[1]

Babak Raji , MSc[1], Martin J. Tenpierik , PhD[1], Andy van den Dobbelsteen , PhD[1]

1) Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, the Netherlands

Abstract

Tall buildings are being designed and built across a wide range of cities. A poorly designed tall building can tremendously increase the building's appetite for energy. Therefore, this paper aims to determine the design strategies that help a high-rise office building to be more energy efficient. For this purpose, a comparative study on twelve case buildings in three climate groups (temperate, sub-tropical & tropical) was performed. The exterior envelope, building form and orientation, service core placement, plan layout, and special design elements like atria and sky gardens were the subject of investigation. The effectiveness of different design strategies for reducing the cooling, heating, ventilation and electric lighting energy were analysed. Finally, lessons from these buildings were defined for the three climates. Furthermore, a comparison of building energy performance data with international benchmarks confirmed that in temperate and sub-tropical climates sustainable design strategies for high-rise buildings were performing well, as a result leading to lower energy consumption. However, for the tropics the design of high-rise buildings needs higher concern.

Keywords

Design strategies for energy efficient tall buildings, building energy performance, sustainability and climate type.

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§ 2.1 Introduction

The construction of tall buildings in our modern cities is increasing in response to several socio-economic and environmental issues. Urban population growth and preservation of green areas, limited land and increasing prices, mature economies and the desire for global competition are some of the reasons for the increased tall building construction. Despite environmental concerns over energy scarcity and global warming, many low-performance tall buildings are emerging to provide cities with additional floor area. These typical air-conditioned glass boxes are not energy efficient in many aspects of their design. This will result in buildings with a high appetite for energy.

Few studies have investigated the impact of design strategies on the energy consumption of high-rise office buildings. Ismail (2007) conducted a comparative study of six Malaysian high-rise buildings (three bioclimatic and three conventional) to investigate the effect of bioclimatic design strategies on users' perception of the indoor environment and on building-related energy use. They found that bioclimatic buildings offer more indoor comfort, improve user's satisfaction and use less energy. In another study, Jahnkassim & Ip (2006), modelled and simulated three bioclimatic high-rises, which were designed by Malaysian architect Ken Yeang, to determine the impact of different design strategies on energy-saving. Comparing the results between the simplified high-rise model (generic option) and bioclimatic model (as designed), they found that the highest energy-saving could be achieved by placing the service core on the hot side and by using external shading devices. The impact of vegetation on energy consumption, they found, was limited to around 0.4% (only including the shading effect of outdoor vegetation and not the evaporative cooling effect). Furthermore, for one of the bioclimatic buildings (Menara Mesiniaga), the impact of recessed sky courts was reported to be negative, adding to the cooling demand.

There is thus still a lack of in-depth studies into the design strategies that can make tall buildings more energy efficient. This paper, therefore, describes the results of a case-study based on multiple high-rise buildings in order to ascertain design strategies that help a high-rise building to be more energy efficient in a temperate, a sub-tropical and a tropical climate. In order to have high performance tall buildings, first there is a need to reduce the building's demand for energy and the most straight forward approach is to design them in a way that reduces their appetite for energy.

§ 2.2 Methodology

This paper is an extension of work originally reported in the Proceedings of the International Conference on Passive and Low Energy Architecture (PLEA) on 6 case buildings and two climate types (Raji et al., 2014). As presented in Figure 2.1, the extended version comprises of twelve case buildings with different degree of sustainability from three climate types (temperate, sub-tropical & tropical) and follows a holistic case-study design with multiple-cases (Yin, 2009). For each climate group, three sustainable high-rises were selected and one typical high-rise design as a reference. This replication logic increased the external validity of this study.

Among others, multiple sources of evidence were used to increase construct validity: building-related energy performance data was collected through a literature review and contact with the energy consultants. The energy data of each group of buildings in one climate (four cases) was compared to analyse the effectiveness of different design strategies in the specific climate type. Finally, lessons from these buildings were defined for the three climates. Furthermore, a comparison with international benchmarks shows the effectiveness of design strategies for each climate. The selection criteria for the sustainable cases were:

- Considered by one of the rating systems or standards for high-performance buildings
- Availability of building-related energy performance data (metered or simulated)
- Newly constructed office building that has been occupied for two years with at least fifteen floors

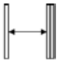
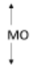
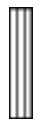
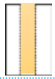
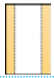
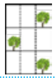
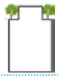
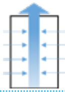
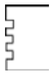
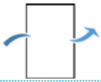
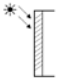
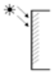
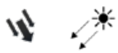
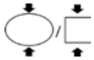
Definitions and methods for calculating the energy use intensity (EUI) vary among countries and legislations. This may cause difficulties when comparing buildings in different countries on energy performance. A building's EUI can be presented in two forms: source energy (primary energy) and site energy (delivered energy). Source energy defines the level of CO_2 emission associated with the energy consumption in a building. Therefore, in some cases, where the energy comes from different sources (renewables or fossil fuels), the primary energy can provide a better understanding of the building's environmental impact. While many other cases use simply site energy. Furthermore, the calculation methods of EUI differ based on the selected floor area. It can be a fraction of the total gross floor area or the net floor area of a building. In this study, we tried to take these differences into account by normalizing the EUI figures among all cases. In this respect, a few conversions were made for making the energy figures comparable. The presented energy figures in this paper, therefore, are site energy in kWh/m^2 of gross floor area.

TOC

Considering the fact that a building's energy performance can be influenced by the decisions made after the construction and the user's behaviour during occupation, the best way to quantify the energy efficiency of a building is by measuring the energy consumption after a certain period of occupation (minimum two years) when the building's operation is balanced appropriately (Gonçalves & Umakoshi, 2010). It is quite probable that when there is a mismatch between the measured and simulated energy performance of a building the influence of the human factor on modelling results was not taken into account. Knowing this fact, this paper aims to focus on case buildings with available measured data. However, buildings' energy performance based on the measured data are either not always available or made publicly accessible. As a result, if measured energy consumption for a building are absent, simulated data are used instead. And where it may impact findings, it is discussed and acknowledged in wthe comparative conclusions.

FIGURE 2.1 Classification of 12 case buildings in temperate, sub-tropical and tropical climate.

ICONOGRAPHY

	Double-skin façade		Manually operated
	Triple-glazed façade		Central atrium or void
	Double-glazed façade		Peripheral atrium
	Single-glazed façade		Indoor sky garden
	Natural ventilation		Sky garden
	Extracted air from indoor		Rooftop shading
	Single-sided and/or cross ventilation + Stack ventilation		Recessed balcony
	Cross ventilation		Recessed green balcony
	Indoor blind within the cavity		Aerodynamic building form
	Indoor blind		Non-aerodynamic building form
	External shading		Environmentally oriented
	Automatically operated		Compact building form

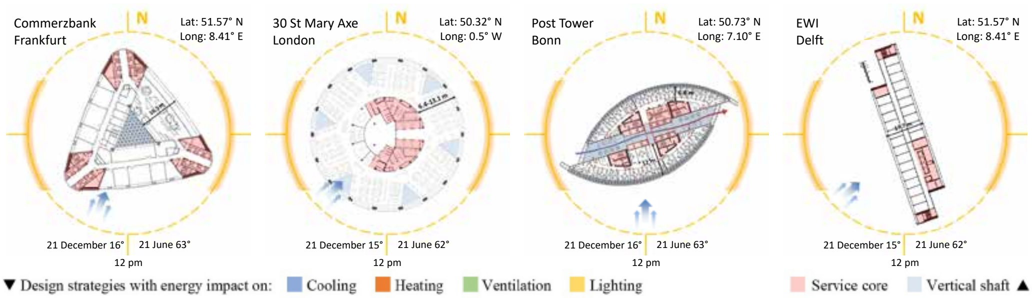
SUBSCRIPTS

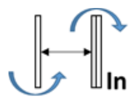
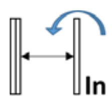
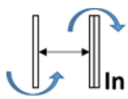
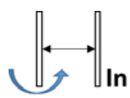
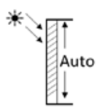
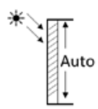
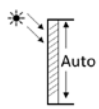
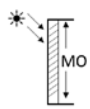
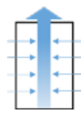
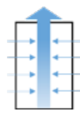
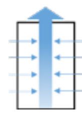
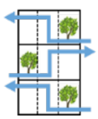
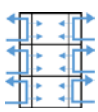
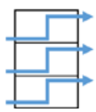
AHU: Air-handling unit
BMS: Building management system
CFD: Computational fluid dynamics
DSF: Double-skin façade
EUI: Energy use intensity
GB: Green balcony

ISG: Indoor sky garden
NT: Natural ventilation
SG: Sky garden
SSV: Single-sided ventilation
WWR: Window-to-wall ratio

§ 2.3 Temperate climate

A comparison of design strategies and energy consumption data for the case buildings in the temperate climate are presented in Figure 2.2 and 2.3 respectively.



Energy impact	Strategies / Cases	Commerzbank	30 St. Mary Axe	Post Tower	EWI
	Façade type				
	Shading				
	NV type				None
	Design strategies assisting in NV				None
	Window-to-wall ratio	58%	100%	100%	80%

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TOC

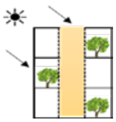
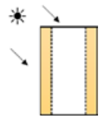
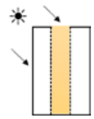
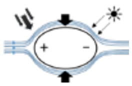
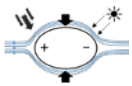
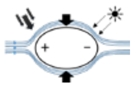
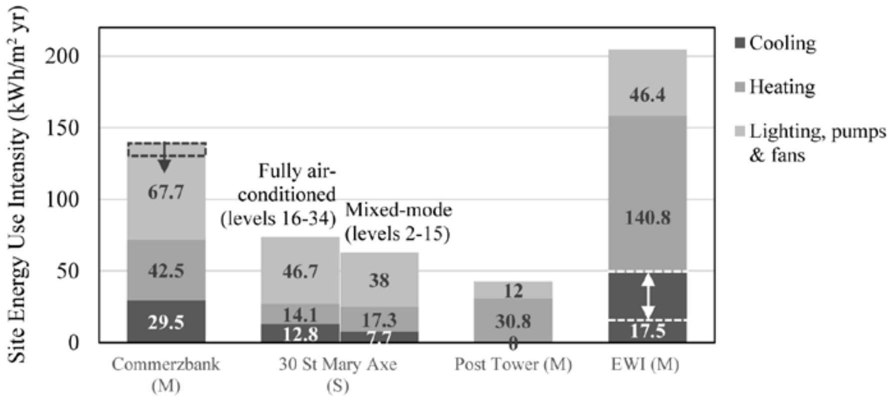
Energy impact				Strategies / Cases	Commerzbank	30 St. Mary Axe	Post Tower	EWI
				Design strategies assisting in day-light control				None
				Service core place-ment				
				Building form and orientation				
				Plan layout	Cellular	Mixed	Cellular	Cellular
				Plan depth	16.5 m from void	6.4-13.1 m from core	12 m from void	17.7 m between facades
				Control of indoor climate	BMS & Occupant	BMS & Occupant	BMS & Occupant	Occupant (limited)
				Thermal buffer spaces	0.2 m DSF cavity	1-1.4 m DSF cavity	1.2-1.7 m DSF cavity	0.95 m DSF cavity
				Summer night-time NV	✓	✗	✓	✗
				Mixed-mode vent	✓	✗	✓	✗
				Greenery system	ISG	✗	✗	✗
				Internal zones with different temp	✓	✗	✓	✗

FIGURE 2.2 A comparative study of design strategies for case buildings in the temperate climate.



(S)=Simulated; (M)=Metered; the electricity consumption is just for lighting, pumps and fans. [1]The EUI for the Commerzbank (Goncalves & Bode, 2010) and the Post Tower (S. Reuss 2014, pers. comm. 19 May) were originally calculated based on the net floor area. To convert the figures from net to gross floor area an efficiency factor (net area/gross area) of 61% & 57% is considered respectively for Commerzbank and Post Tower. In addition, a very small amount of the cooling load is combined with the electricity usage in the Commerzbank building that should be negligible. [2]The energy consumption at 30 St Mary Axe (N. Clark 2014, pers. comm. 12 May) is based on simulations of two scenarios: a fully air-conditioned design on levels 16-34 and a mixed-mode design on levels 2-15. The energy source at EWI building is provided by electricity from the grid, district heating and a ground-coupled heat pump system (W. van Rijsbergen 2014, pers. comm. 4 Aug).
Detailed information regarding the weather file, heating degree days (HDD) and cooling degree days (CDD) of each case study/city are presented in the table below.

CASE STUDY / CITY	COMMERZBANK / FRANKFURT	30 ST MARY AXE / LONDON	POST TOWER / BONN	EWI / DELFT
Year	2008	IWEC*	2003	2013
HDD	2750	2300	2786	2631
CDD	396	185	269	184

*IWEC: International Weather for Energy Calculation (US Department of Energy). *For energy simulations, a dynamic method based on hourly values was employed and the energy results were generated from IWEC weather data for each location. HDD and CDD data were obtained from BizEE Software Ltd.*

FIGURE 2.3 Energy performance data of the temperate cases for one year.

Cooling

Among the cases studied in a temperate climate, the Post Tower has the lowest energy consumption for cooling from the grid by around zero. Thermally active ceilings and decentralized supplementary fan coil systems provide cooling for this building. The cold water required for cooling is supplied by the Rhine River and a sunk well. This eliminates the need for cooling by chillers. The electricity to drive the pumps is the

TOC

only requirement for providing cooling (Welfonder, 2006). Furthermore, the building is oriented based on the sun path with the long axis almost along east-west which reduces the solar heat gain. Mary Axe can be ranked second best, with an electricity consumption in a range between 7.7-12.8 kWh/m^2 for cooling. The energy consultants for this building have considered two scenarios for air-conditioning, a mixed-mode zone (a combination of mechanical and natural ventilation during different times a year) and a fully mechanically conditioned zone, respectively for the levels 2-15 and 16-34. The simulated results show that the cooling demand is lower for the mixed mode zone (7.7 kWh/m^2) compared to entirely mechanically conditioned zone (12.8 kWh/m^2). Commerzbank's energy consumption for cooling is around 29.5 kWh/m^2. Absorption chillers generate cold water and chilled ceilings distribute this above the conditioned spaces. In addition, the building uses natural ventilation up to 80% of the year which reduces the need for air-conditioning effectively. Commerzbank and Post Tower are also equipped with other energy-efficiency strategies such as a double-skin façade with ventilated cavity, motorized blinds for solar control, and summer night-time ventilation. A building management system (BMS) controls the operation of blinds and openings, which can be overridden by the occupants to customize the climate to their desires. The total energy consumption of all of the 3 sustainable buildings is considerably less than of typical air-conditioned buildings in the same climate.

In contract, the EWI building of Delft University of Technology is a conventional high-rise building. The building has benefitted from some of the features of sustainable buildings, like a narrow plan and a double-skin façade. On the other hand, inefficient natural ventilation inside the cavity of the double-skin facade and no operable windows limit the effectiveness of these strategies. Cooling is generated by a ground-coupled heat pump system. Cold water is used to cool air in plant rooms which is then distributed to cellular offices. Backup air-handling units (AHUs) are used for spaces with higher cooling demand like lecture halls and labs. Since the air supply ducts are placed inside the cavity of the double-skin facade, the chilled air is pre-heated along its way to the rooms. Therefore, the efficiency of this cooling system is low and as a result, the electricity demand for cooling high. For solar protection, Venetian indoor blinds are adjusted in the cavity and occupants can control manually the radiation intensity in each office. Since the energy use for cooling is partly being provided by the ground-coupled heat pump system (17.5 kWh/m^2) and the rest by the city grid, the total consumption for cooling is unknown. However, the mild summers in Delft lead to a low cooling demand of this building.

Heading

Considering heating, the Mary Axe building has the lowest energy consumption among the temperate cases. Fresh air for mechanical ventilation is drawn through the narrow slits between the glazing panels, then conditioned by the AHUs and finally distributed through adjusted ducts at ceiling level. Part of the exhaust air from the offices ventilates the cavity inside the facade (Jenkins, 2009); therefore, in winter, the cavity will have a temperature similar to that of the indoor air and the building's transmission losses will decrease. Simulation results show that the heating demand is slightly higher when introducing natural ventilation (17.3 kWh/m^2) into the building compared to a fully air-conditioned mode (14.1 kWh/m^2). The Post Tower can be ranked second best with an energy consumption for heating of around 30.8 kWh/m^2. Waste heat from electricity production (district heating) is the energy source for heating. The deep cavity (120-170 cm) of the double-skin façade acts as a thermal buffer between the outdoor and the indoor air. On cold winter days, fresh air first is warmed up in the double-skin façade before it enters the perimeter fan coil units; thus, reducing the need for heating. The energy consumption for heating of the Commerzbank is 42.5 kWh/m^2, higher than of the Mary Axe and the Post Tower. Heating is provided by the local district heating network and is distributed through thermostatically operated radiators. The double-skin façade of this building has the narrowest cavity (20 cm) among the three buildings. However, window-to-wall ratio, which strongly influences the amount of solar heat gain versus the transmission losses through the envelope, is considerably lower in the Commerzbank (58%) than of the other sustainable cases (100%).

From the total energy use of the EWI building, more than half of it is consumed for heating. The heating source is a combination of local district heating (124.8 kWh/m^2) and a ground-coupled heat pump system (16 kWh/m^2). The double-skin façade with 95 cm cavity should act as a thermal buffer for office areas but the high amount of heating demand shows that this façade is underperforming. A poor performance single-glazed curtain wall with high infiltration and a cavity that is always vented with outside air (also in winter) are the reasons for high heating demand at the EWI building. Additionally, heating systems (hot-water radiators) are installed directly behind a single-glazed façade along the hallway which means a lot of heat loss through this thin layer of glass.

Ventilation

Interestingly, all selected sustainable buildings in the temperate climate, use both natural and mechanical ventilation. However, the duration and place of using natural ventilation varies depending on the design and the interior plan configuration. In case of the Commerzbank, inward-facing offices that use tempered fresh air from sky gardens and the atrium can be naturally ventilated throughout the entire year; though, the outward-facing offices with direct access to fresh air can utilize natural ventilation for about 80% of the year (Jenkins, 2004). For the Post Tower, a combination of cross and stack ventilation provides all working areas and communal spaces with fresh air naturally. Only interior meeting rooms and conference halls are conditioned mechanically. Outside air enters the building through the double-skin façade, flows from the offices into the corridors and then is exhausted through the sky gardens. In addition, the outer skin of the façade is extended to create an aerodynamic form which increases the ventilation rate (Dassler et al., 2003). In both projects, the double-skin façade is naturally ventilated and night-time ventilation is applied during summer. The office areas in the Mary Axe building are not ventilated directly through the façade. Fresh air first comes into 6 peripheral atria through small openings in the façade before this tempered air is distributed to the working areas. For the original design, it was predicted that the office areas could be naturally ventilated without heating and cooling during 41-48% of the year. But with a change from owner occupation to multi-tenant occupation, most tenants rejected the energy-efficiency package with automated windows and choose for the year-round air conditioning package instead (Wood & Salib, 2013a). However, the central service core needs to be mechanically ventilated due to a deep plan (13.1 m from central core at middle floors). The cavity inside the facade is not ventilated with fresh air but with extracted air from the offices. Furthermore, the building does not use summer night-time ventilation.

The construction of the EWI building dates back to the 1960s when the development of double-skin façade technology was in its infancy. The air inlets for natural ventilation are placed in the middle of the façade but the air outlets are at the end of the facade. In summer, hot air in the cavity must run to the end of cavity to be exhausted. Therefore, ventilation in the cavity is hardly working even with the help of two exhaust fans inside the cavity. As a result, part of the heat is transferred from the cavity to the office spaces through a single-pane window increasing the cooling load of the building. Interior spaces are equipped with mechanical ventilation. Since, no separate ventilation is considered for corridors, part of the extracted air from the offices (30%) is transferred to temper the circulation areas while the rest is exhausted through the rooftop.

Lighting

The Commerzbank has the highest building-related electricity consumption (67.7 kWh/m^2) among the cases in the temperate climate. As it is not clear how much of this energy is used for lighting (separate from pumps and fans), it is difficult to determine the causes for this: it might be a result of a prestigious design, higher number of

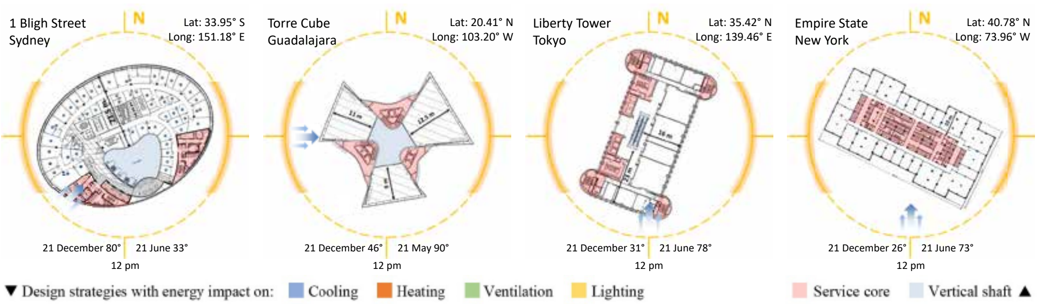
TOC

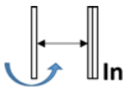
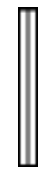
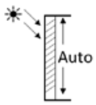
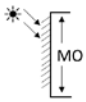
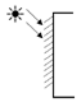
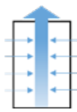
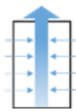
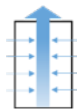
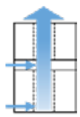
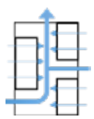
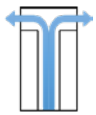
occupants per square meter or architectural design features like window-to-wall ratio and plan depth. Considering the façade transparency, the Commerzbank has the lowest window-to-wall ratio of approximately 58%. This could mean that there is more need for artificial lighting. However, a full height central atrium and 9 spiral sky gardens bring a lot of natural light deep into the building interior. In the Post Tower, around 85% of the working stations are located within 5 meters from the external façade. Using daylight for the majority of office spaces resulted in a significant reduction of energy demand for artificial lighting. Additionally, most of the central meeting rooms and service spaces are faced toward a full-height atrium and can be naturally lit. The office spaces operate in stand-by mode when the rooms are empty. Of the total electricity consumption, lighting is 6.2 kWh/m^2 (Welfonder, 2006). In the Mary Axe building, the distance between the core and perimeter ranges from 6.4 to 13.1 m depending on the floor. This building thus has a deeper plan compared to the other cases. However, the problem of a deep plan is solved here with the help of 6 triangular atria along the building perimeter. The six rectangular office fingers can be naturally lit from three directions. The big central service core should always be artificially lit due to its central positioning. The total electricity consumption for lighting are respectively 26.4 and 29.1 kWh/m^2 for the mixed-mode (levels 2-15) and the fully mechanically conditioned (levels 16-34) zones (N. Clark 2014, pers. comm. 12 May).

The EWI building's electricity consumption for lighting, pumps and fans is around 46.4 kWh/m^2. Part of the cooling load is also combined with the electricity usage. Considering the educational function of this building with some labs and lecture halls, the energy use for lighting would be in an acceptable range (24.7 kWh/m^2). However, from the total floor area of this building, just the first three storeys are used for educational purposes while the upper floors are used as offices with cellular work areas. A narrow plan depth beside the peripheral arrangement of office spaces within six meters from the external façade are effective strategies for reducing the energy demand for lighting.

§ 2.4 Sub-tropical climate

A comparison of design strategies and energy consumption data for the case buildings in the sub-tropical climate are presented in Figure 2.4 and 2.5 respectively.



Energy impact	Strategies / Cases	Commerzbank	30 St. Mary Axe	Post Tower	EWI
	Façade type				
	Shading				None
	NV type				SSV (limited)
	Design strategies assisting in NV				None
	Window-to-wall ratio	100%	35%	25%	20%

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TOC

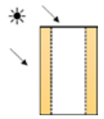
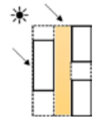
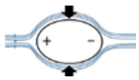
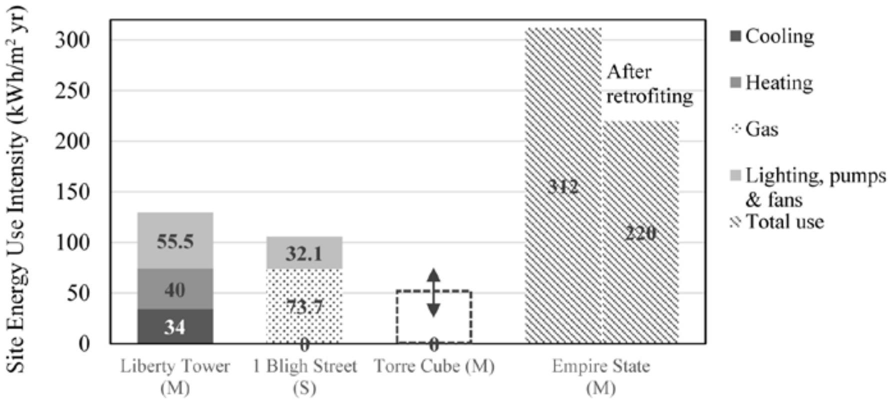
Energy impact	Strategies / Cases	Commerzbank	30 St. Mary Axe	Post Tower	EWI
	Design strategies assisting in day-light control			None	None
	Service core place-ment				
	Building form and orientation				
	Plan layout	Cellular	Open plan	Mixed	Mixed
	Plan depth	23.5 m from void	9–12.5 m from void	25 m from void	10 m from core
	Control of indoor climate	BMS	Occupant	BMS	Occupant (limited)
	Thermal buffer spaces	0.6 m DSF cavity	Peripheral multi-ple-cores	None	None
	Summer night-time NV	✗	✗	✓	✗
	Mixed-mode vent	✗	✗	✓	✗
	Greenery system	✗	✗	✗	✗
	Internal zones with different temp	✓	✗	✗	✗

FIGURE 2.4 A comparative study of design strategies for case buildings in the sub-tropical climate.



(S)=Simulated; (M)=Metered; the electricity consumption is just for lighting, pumps and fans. [1]The energy consumption of the Liberty Tower (Kato & Chikamoto, 2002) is converted from primary energy to delivered energy with an average efficiency factor around 45.4% for power plants in Japan. The conversion was calculated based on the average energy efficiency of power plants for electricity generation from local primary energy sources for the same year the Liberty tower's energy consumption was measured. [2]1 Bligh Street (Yudelson & Meyer, 2013) building use a tri-generation system for combined cooling, heating and electricity generation. The projected energy sources are gas and electricity. However, it is not clear how much is used to generate heat or lighting. [3]Torre Cube (Wood & Salib, 2013b) does not rely on an air-conditioning system for cooling, heating or ventilation. Therefore, the thermal energy consumption is zero in this building. The electricity consumption for lighting and equipment has not been published for this building. Therefore, the predicted consumption is presented with a dashed line. [4]The energy consumption data for the Empire State (Johnson Controls, 2013) is the total metered energy use before and after the retrofitting program.
Detailed information regarding the weather file, heating degree days (HDD) and cooling degree days (CDD) of each case study/city are presented in the table below.

CASE STUDY / CITY	LIBERTY TOWER / TOKYO	1 BLIGH STREET / SYDNEY	TORRE CUBE / GUADALAJARA	EMPIRE STATE / NEW YORK	
Year	2000	IWEC*	IWEC*	2007	2012
HDD	1417	580	534	2355	2286
CDD	1003	1000	1361	828	954

*IWEC: International Weather for Energy Calculation (US Department of Energy). *For energy simulations, a dynamic method based on hourly values was employed and the energy results were generated from IWEC weather data for each location. HDD and CDD data were obtained from BizEE Software Ltd.*

FIGURE 2.5 Energy performance data of the sub-tropical cases for one year.

Cooling

Among the cases from the sub-tropical climate, Torre Cube has the lowest energy consumption for heating and cooling (0 kWh/m²) since it does not depend on an air-conditioning system. Due to the mild climate in Guadalajara, buildings in this city can be naturally ventilated throughout almost the entire year if designed well. Solar radiation intensity, however, is very high making sun-shading an essential strategy to keep the building's cooling demand low. Adjustable external screens besides minimizing the proportion of window-to-wall ratio by around 35% are the two main strategies that protect this building from excessive heat gain in summer. The 1 Bligh Street building in Sydney is equipped with a hybrid tri-generation system that simultaneously generates heat, cold and electrical power. In this building, 500 m^2 of the roof is covered with solar collectors that feed the absorption chiller to generate cold (Lehmann & Ingenhoven, 2009). Therefore, the building does not use electricity from the grid for cooling. Furthermore, the compact elliptical form has 12% less surface area exposed to the outdoor climate than a rectilinear building of the same volume (Yeang, 2008) thus reducing the heat gains and losses through the building envelope. In addition, a high-performance naturally ventilated double-skin façade with 60 cm cavity helps to reduce the heat transfer through the envelope. However, there is some debate considering the land use and ecology of this building. The building's orientation and configuration of plan are mainly derived from the urban grid and the desire to maximize the view, not from environmental concerns. While the service core could have been used as solar buffer on the hot east and west sides, it is placed on the south side (non-harbour side of the floor plate). The Liberty Tower in Tokyo has a higher occupancy rate due to its educational function, thus a higher cooling demand compared to an equivalent office building. The building uses around 34 kWh/m^2 for cooling which is higher than the other two sustainable buildings. However, the 1 Bligh Street building's dependence on renewable energy (solar energy) for cooling does not mean that the cooling demand of this building is less than of Liberty Tower. This building does not seem to be oriented environmentally. The majority of lecture rooms are facing (south)east whereas the opposite (north)west contains the majority of service areas. Vertical and horizontal concrete fins on the façade protect the openings from high solar gains in summer.

In the sub-tropical climate, the Empire State building represents a traditional high-rise building design with a central service core that is fully air-conditioned and not oriented environmentally. Prior to refurbishment in 2009, the building's total energy consumption was 100 kWh/m^2 higher than the median energy consumption of office buildings in the US. However, an innovative energy-saving retrofitting program reduced the building's total energy consumption by 38% which also led the building to receive a gold certification under the LEED rating system for operation and maintenance in the year 2011. Some of the effective strategies for reducing the cooling load include improved insulation of existing windows (gas-filled and use of coated film), retrofitted chiller plants and replacement of old air handling units with fewer and more efficient units. Furthermore, providing tenants with access to online energy consumption and benchmarking information encourages them to be more energy conscious.

Heading

As mentioned before, Torre Cube has zero energy use for heating due to the mild weather conditions in Guadalajara. During the cold months (December and January) the daily mean temperature is around 17 °C (See appendix 1). This means that the internal and passive solar heat gains are sufficient to warm up the small interior office spaces. Liberty Tower's heating load is around 40 kWh/m^2. The rectilinear shape of this building increases the exposed surface area and therefore the heat losses through the envelope. Based on computer simulation analysis of the design proposal, the 1 Bligh Street building uses 73.7 kWh/m^2 of gas to feed a gas-fired tri-generation system which generates electricity and useful heat. This system is up to 50% more efficient compared to conventional grid-connected systems. From the waste heat, 'free' cooling and hot water can be generated. The office spaces are fully air-conditioned and separated from the atrium by glass walls. Extracted conditioned air from the offices is used to temper the naturally ventilated atrium. However, the building's energy use for heating, which is part of the 73.7 kWh/m^2, has not been published.

Also, the figures for the heating energy demand of the Empire State building are not published separately, but the total amount of energy consumption of this building is the highest among the sub-topical cases, even after the retrofitting program. This result emphasises the fact that the most effective strategies contributing to energy-saving of building design are those applied before construction.

Ventilation

1 Bligh Street has two separate ventilation strategies. The communal heart of the building is naturally ventilated but the working areas are fully mechanically ventilated. Natural fresh air is provided through an opening on the ground floor and a sky garden on the 15th floor and is distributed on all floors by stack ventilation in a full height atrium. The building is designed in a way that the perimeter cellular offices may potentially use single-sided natural ventilation if the interior glass panels are replaced with operable ones. But the deep floor plan does not allow for cross ventilation. This is an example of a building design on which changes in tenancy patterns and the consequent different space usage were accounted for in the design stages, in spite of the fact that it is just limited to the perimeter cellular offices. With the help of natural ventilation, the annual cooling demand of Liberty Tower was reduced by 17% (Kato & Chikamoto, 2002). Two architectural elements that effectively have improved this natural ventilation strategy are the escalator void and a wind floor on the 18th floor on top of the circulation shaft. CFD analysis has shown that the wind floor increases the air flow rate by 30% (Chikamoto et al., 1999). As the escalator void is not segmented,

there is a risk of an extreme stack effect and draft inside the building. Furthermore, the introduction of fresh air directly into the working areas might provide discomfort especially for the occupants sitting near the air inlets. In the Liberty Tower, cool fresh air comes in directly through the inlets below the fixed windows. The inability of the occupants to control their operation (fully controlled by a BMS) may limit their comfort and may result in user dissatisfaction (cold feet) (Wood & Salib, 2013c). The Torre Cube building uses different architectural elements to provide both cross and stack ventilation. Fan-shaped office wings help to funnel the air across the working spaces before it is exhausted through a central open void. Three open spiral sky gardens lead to a higher air circulation in the void. However, without a CFD analysis it is not clear if the sky gardens have a positive or a negative effect on buoyancy in the central void.

Similar to other traditional high-rises, the Empire State building is fully dependent on mechanical ventilation with no air inlets or operable windows for introducing natural ventilation into the building. However, after the retrofitting program the building was equipped with CO_2 sensors for the control of the ventilation demand.

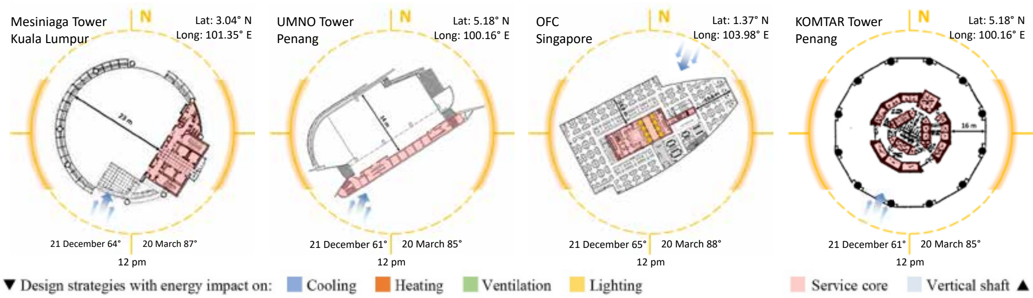
Lighting

1 Bligh Street has a fully transparent façade. Due to a deep plan (23.5 m from façade to central void), there are three working zones between the building perimeter and the atrium which means just 30% of permanent working stations are within 5 meters of this façade. A central atrium and transparent partitions are used to increase natural light penetration. Temporarily used spaces like meeting rooms are placed in the mid-zone. The figures of electricity consumption for lighting, fans and ventilation are not available separately but the total delivered electricity is around 32.1 kWh/m^2. Torre Cube's electricity use for lighting has not been published. Because of a central void, the office wings in this building receive daylight from two sides, which allows for a deep office plan of about 9-12.5m. The electricity use for lighting and pumps of Liberty Tower is around 55.5 kWh/m^2. In comparison with 1 Bligh Street, the Liberty Tower and Torre Cube have considerably lower window-to-wall ratio of around 25% and 35% respectively.

The construction of Empire State building dates back to 1931 when high-rise building design was mostly affected by the 1916 zoning law (typical wedding cake buildings with series of setbacks) and prior to the development of the glazed curtain walls in 1951 (Oldfield et al., 2008). Therefore, façade transparency is lower (WWR: 20%) as compared to the other cases in the sub-tropical climate. However, due to the New York zoning law (1916), no office space is deeper than 8.5 meter; thus, the slender shape of this building provided greater natural light penetration compared to the compact prezoning law buildings. Outfitting offices with occupancy sensors, better lighting controls, and layouts that maximize natural daylight were part of the retrofitting program for improving the energy-efficiency.

§ 2.5 Tropical climate

A comparison of design strategies and energy consumption data for the case buildings in the tropical climate are presented in Figure 2.6 and 2.7 respectively.



Energy impact	Strategies / Cases	Mesiniaga	UMNO	OFC	KOMTAR
	Façade type				
	Shading			Auto	None
	NV type			None	SSV (limited)

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TOC

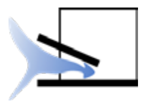
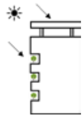
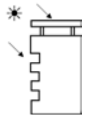
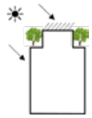
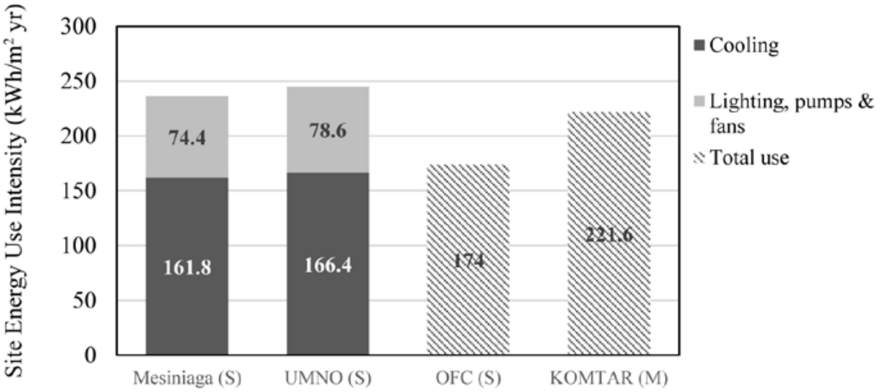
Energy impact	Strategies / Cases	Mesiniaga	UMNO	OFC	KOMTAR
	Design strategies assisting in NV	None		None	None
	Window-to-wall ratio	65%	60%	100%	80%
	Design strategies assisting in day-light control				None
	Service core place-ment				
	Building form and orientation				
	Plan layout	Open plan	Open plan	Open plan	Mixed
	Plan depth	23 m from core	14 m from core	13.8–19.8 m from core	16 m from core
	Control of indoor climate	Occupant	Occupant	BMS	Occupant (limited)
	Thermal buffer spaces	Service core (east side)	Service core (east side)	None	None
	Summer night-time NV	✗	✗	✗	✗
	Mixed-mode vent	✗	✗	✗	✗
	Greenery system	GB	✗	SG	✗
	Internal zones with different temp	✓	✓	✗	✗

FIGURE 2.6 A comparative study of design strategies for case buildings in the tropical climate.



(S)=Simulated; (M)=Metered; the electricity consumption is the total usage for lighting, pumps and fans. [1]The yearly electricity consumption for the Mesiniaga Tower (Jahnkassim, 2004), the UMNO Tower (Jahnkassim, 2004) and the OFC (Keppel Land, 2011) are simulated energy - all the three cases were employed a dynamic method based on hourly values - but for the KOMTAR Tower (Ismail, 2007) is metered energy.
Detailed information regarding the weather file, heating degree days (HDD) and cooling degree days (CDD) of each case study/city are presented in the table below.

CASE STUDY / CITY	MESINIAGA / KUALA LUMPUR	UMNO / GEORGE TOWN	OFC / SINGAPORE	KOMTAR / GEORGE TOWN
Year	IWEC*	IWEC*	IWEC*	2004
HDD	0	0	0	0
CDD	3730	3690	3730	3727

*IWEC: International Weather for Energy Calculation (US Department of Energy). *For energy simulations, a dynamic method based on hourly values was employed and the energy results were generated from IWEC weather data for each location. HDD and CDD data were obtained from BizEE Software Ltd.*

FIGURE 2.7 Energy performance data of the tropical cases for one year.

Cooling

In a tropical climate, cooling and lighting are the two largest contributors to the total energy use for an office building. For the Ocean Financial Centre (OFC), cooling is provided by a hybrid chilled water supply and the district cooling system. The building's external shell is entirely covered by a triple-glazed glass facade with low-e coating and solar control film. Automatically adjusted indoor blinds let the natural light come in but prevent unpleasant glare. As a result, the transmission gains through the envelope of OFC are 15% less (Keppel Land, 2011) compared to a standard value for the same location (50 W/m²). However, even a very high-performance glazing still allows about one-third of the sun's heat to enter the building. Therefore, a fully glazed façade might increase the cooling demand. The building's form and orientation are suboptimal from an energy-efficiency perspective since they were derived solely from the city grid and the aim to maximize the view to the harbour. The central positioning of the service core and the use of the hot sides of the building as permanent work areas leads to an extra energy demand for cooling. The energy consumption for cooling is not published separately, however the total energy consumption is less than of the other cases in the tropical climate.

Simulations showed that the energy consumption for cooling of the Mesiniaga Tower is around 161.8 kWh/m^2. The building's circular shape allows for the smallest surface exposure to the outdoor climate (25% less compared to a rectilinear form with the same volume) (Yeang, 2008); therefore, lower thermal transfer through the envelope. External shading along the perimeter (with higher coverage on the west side) and the placement of the service core approximately towards east are two important strategies for reducing the solar heat gains on the hot sides of this building. Recessed terraces are another strategy for providing deep permanent shading. Buffer spaces, such as service areas placed along the perimeter of the building, could reduce the amount of glazing thus reducing solar heat gains. Additionally, such placement provides the possibility of using natural ventilation and daylight in these service areas. In the tropics, surface to volume ratio is an important factor which determines the amount of external heat gains. Therefore, it is important to find a balance between the shading by recessed balconies and the increased external envelope surface. Balconies should be placed such that they cut off direct radiation during the hot hours of the day. Otherwise the effect of heat transfer through the increased surface will offset the shading effect by recessed terraces. Random placement of balconies similar to the spiral recessed terraces of the Mesiniaga Tower, could increase the energy demand in comparison with the simple cylindrical model for this building. According to simulations by Johnkassim & Ip (2006), a slight reduction of the cooling demand (1-2%) was observed for the compact cylindrical form without spiral balconies.

The UMNO Tower can be ranked third with an energy consumption for cooling of around 166.4 kWh/m^2 slightly higher than of the Mesiniaga Tower. For the original design, a natural ventilation strategy for the full year was proposed with a provision for tenants to install AHUs. However, after the construction, natural ventilation was applied only to the circulation area and the lift lobbies. Partition walls between the spaces were added and a floor-by-floor basis air-conditioning system was installed. Due to site limitations, the building could not be oriented to the direction of the prevailing wind. As a result of that, two wind wing walls were developed to catch and lead the wind into the building. The location of the service core with a thick concrete wall along the south-east façade allows to act as a thermal buffer on the hot side and reduces the cooling load significantly by 12%. Multiple balconies on the west side help to cut off direct radiation at critical hot hours with a positive impact on cooling reduction by about 4% in the UMNO (Johnkassim & Ip, 2006). External shading screens are more closed towards the west and more transparent towards the north. The rooftop is also covered by a large curved canopy which blocks the roof from direct solar radiation.

The KOMTAR Tower is an example of a typical high-rise building that is fully air-conditioned, that has a facade almost completely covered with full height single layer glass and has a central service core. The floor plan of the building is a 12-sided polygon and is identical on all sides. The window to wall ratio is around 80% while there is no external shading device or recessed terrace to shade the facade. However, the building is equipped with manually controlled indoor blinds that also block the view. Surprisingly, the metered energy data for this building shows a different trend. The cooling load is not available separately but the total energy use of the KOMTAR Tower is less than of both Mesiniaga and the UMNO Tower, two of the sustainable high-rises. One reason could be that the KOMTAR's reputation is currently dropping as a result of poor maintenance and lack of facilities in competition with fancier modern buildings in its vicinity. Therefore, the KOMTAR tower has a few unoccupied floors and that for calculating the EUI these floors are included. Whereas the other two sustainable buildings are fully occupied.

Heating

In equatorial areas, the average annual temperature is almost constant throughout the year around 30 °C, which means there is no need for heating.

Ventilation

The office areas in the Mesiniaga Tower are mostly air-conditioned and only the service core is naturally ventilated. Since the natural ventilation strategy mainly relies on cross-ventilation, it is difficult to provide an acceptable air flow rate along the plan (30 m plan diameter). However, the use of two wind wing walls at UMNO Tower, resulted in a higher indoor air flow rate in this building and a wider range of wind directions being captured. Similar to the Mesiniaga Tower, in the UMNO building, the service area is naturally ventilated but the office areas are mostly mechanically ventilated. In both projects there is no BMS to control the operation of openings. Therefore, it might cause problems in attaining the required airflow rate needed for ventilation especially in this humid tropical climate. KOMTAR and OFC are both fully mechanically ventilated except for two mechanical floors in OFC that have air inlets for natural ventilation. Furthermore, the service core in this building also do not have this potential to be naturally ventilated due to its central positioning.

Lighting

The OFC has the highest façade transparency among the four cases studied in the tropical climate. The rooftop is equipped with 400 m^2 of PV cells which not only shade the roof and provide a communal space but also produce enough renewable energy to provide electricity for lighting more than 4,500 m^2 of office space. The energy consumption for lighting has not been published but the total energy use is 174 kWh/ m^2. The building is equipped with energy-saving technologies such as high-efficiency lighting and motion sensors for all of the working stations and service areas, and a regenerative drive lift system that has 75% higher efficiency compared to conventional lifts. However, a deep plan which exceeds to more than 20 m in some floors resulted in a higher demand for artificial lighting specifically for the central service core.

Although the total energy consumption of the Mesiniaga Tower is lower than of the UMNO Tower, the electricity usage is slightly higher. The reason can be due to a deeper plan of Mesiniaga (23 m) compared to UMNO (14 m). In both of the projects the façade transparency is around 80% on all sides except east (Ismail, 2007) and the service core is positioned on the southeast side. Spiral recessed terraces in Mesiniaga bring daylight deeper into the plan which can ameliorate the negative effect of the deep plan.

Considering European standards for office buildings, permanent working areas should not be located farther than 8 m from the facade. Although the plan depth of KOMTAR is 16 m from façade to central core the illuminance level in the offices is measured to be 4 times higher than recommended and is between 4000-4500 lux (Fairuz Syed Fadzil & Sia, 2004). Furthermore, the central service core increases the energy demand for artificial lighting.

§ 2.6 Lessons learned: Effective design strategies for high-rises

This section provides design recommendations for reducing the energy consumption of high-rise office buildings in temperate, sub-tropical and tropical climates. These recommendations are based on a combination of literature review on passive design techniques and the lessons learned from the analysis of high-performance design references.

§ 2.6.1 General design strategies for high-rise office buildings

Concerning plan configuration, it is important to place the permanent work stations close to the envelope to reduce the need for artificial lighting. Dividing the internal zone into areas with different temperature is another important strategy that can reduce the cooling/heating load of high-rise buildings. Office workers expect a high degree of comfort in their work stations but tolerate a little bit of discomfort in lift lobbies and communal spaces.

Plan form and building shape (or compactness) can influence the amount of heat gain or loss through the envelope. Circular and elliptical forms have an exposed surface area that is respectively 25% and 12% less than of a rectilinear building of the same volume. Furthermore, an aerodynamically curved form minimizes wind turbulence and downdraft at street level.

Furthermore, the effectiveness of natural ventilation and daylight depends strongly on how the openings and solar shading devices are controlled. The absence of a central BMS might cause problems in attaining the right adjustments for providing indoor comfort conditions and may increase the energy consumption. Smart occupancy sensors cut down unnecessary consumption for lighting, and mechanical ventilation. In cellular offices, it is important that occupants can override the BMS to ensure their individual comfort. Psychologically, occupants with more control over their environment are more tolerant to high or low temperatures. However, the BMS should automatically switch off the air-conditioning system if occupants decide to open the window.

§ 2.6.2 Design strategies for high-rise office buildings in a temperate climate

Façade transparency and plan depth are the two dominant factors with great influence on the electricity demand for lighting. A fully transparent façade is a common strategy in a temperate climate. However, it is important to provide a balance between the use of daylight, the solar heat gain in summer and the heat loss in winter. A double-skin façade with a deep cavity is an effective strategy for reducing the cooling and heating loads of high-rise buildings in temperate climates. A double-skin façade can act as a thermal buffer between the outdoor and indoor environment. The deep cavity ensures that in summer solar radiation does not enter the office spaces. Moreover, offices next to this façade can use natural ventilation for a longer period of time if fresh air first passes through the cavity in the double-skin façade before entering the offices. However, an effective ventilation strategy is highly needed inside this cavity especially during summer; otherwise the double-skin façade would act like a greenhouse and transfer a lot of heat into the building. Solar control devices within the cavity, like motorized venetian blinds, allow for passive heating in winter but prevent unpleasant glare and overheating in summer.

A mixed-mode (natural and mechanical) ventilation strategy can reduce effectively the energy demand for cooling and mechanical ventilation. Some architectural elements that can help the air intake, circulation and exhaust are sky gardens and vertical shafts like atria and circulation voids. When using a full-height atrium, there is a risk of high temperature differences and extreme stack effects and drafts. For controlling this excessive stack effect, a full-height atrium is usually segmented into smaller zones with lower pressure difference.

§ 2.6.3 Design strategies for high-rise office buildings in a sub-tropical climate

In a sub-tropical climate, solar radiation intensity is high. Therefore, the most effective design strategies are those that reduce the solar heat gain. Such strategies include limited façade transparency on the east and west side of the building, the placement of service cores on the hot sides (double-sided core on east and west) and the extensive use of shading devices. Glazing type is usually double-glazing with low-e coating.

Placing the work stations along the north and south façade is a good strategy for reducing the electricity demand for artificial lighting. However, the size and position of openings should protect the occupants form direct solar radiation and glare. Using external shading and indoor blinds improves the quality of daylighting.

Similar to a temperate climate, natural ventilation is also an effective solution for reducing the cooling demand in a sub-tropical climate. However, introducing humid outdoor air may reduce thermal comfort of the occupants as a result of which constant humidity control is an essential element of such a strategy.

§ 2.6.4 Design strategies for high-rise office buildings in a tropical climate

Intense radiation, high humidity, low wind speeds and a constant high air temperature throughout the year are significant climatic features in the tropics. The best energy-saving strategies for reducing the cooling load are those that limit heat gains. Shading the envelope (external devices or application of greenery systems), placing service areas as a thermal buffer on the hot sides with limited openings, using reflective external materials and finally minimizing surface to volume ratio are some of the strategies to control the heat gain. Shadings should be more obstructing towards the hot sides and more transparent on the other sides. Due to the high sun angle in these areas, it is also important to shade the roof and utilize energy generation systems like solar collectors or PV panels to compensate for the excessive cooling demand.

Multiple recessed terraces in the tropics act like sky gardens in a temperate climate. They are incorporated into the building design to provide solar shading and a communal space where occupants can enjoy the cool breeze. They also provide the possibility of making full height openings for bringing daylight deeper into the plan while shading the openings entirely. Moreover, they act as buffers with adjustable windows to control the rate and distribution of natural ventilation. In case of using recessed terraces, it is better to place them in directions that receive the highest radiation to limit heat gain during critical hot hours.

Natural ventilation can be utilized as an effective backup system in communal spaces and service areas but rarely for permanent working stations that seek higher comfort conditions. Due to low wind speeds, the application of architectural elements, such as wind wing walls, voids or an aerodynamic building form, is necessary to increase the air flow rate inside the building.

§ 2.7 Comparison with energy benchmarks

The total energy use of twelve case studies and related energy benchmarks in each climate/context are presented in Figure 2.8. Considering the energy standards in Germany & the UK for a naturally ventilated and heated building (123-135 kWh/m^2), the EUI of two cases in a temperate climate, 30 St Mary Axe and the Post Tower, are below the local benchmarks. The total energy consumption of the Commerzbank is around 140 kWh/m^2 which is slightly higher than the UK & German standards for a naturally ventilated building. As a reference for typical high-rise design, the energy consumption at the EWI building is more than sustainable case buildings in temperate climate. However, the total energy use is below the standards for a mechanically ventilated building in Germany. This relatively lower energy consumption results from special design strategies such as a narrow plan and a supplementary ground-coupled heat pump system for heating and cooling.

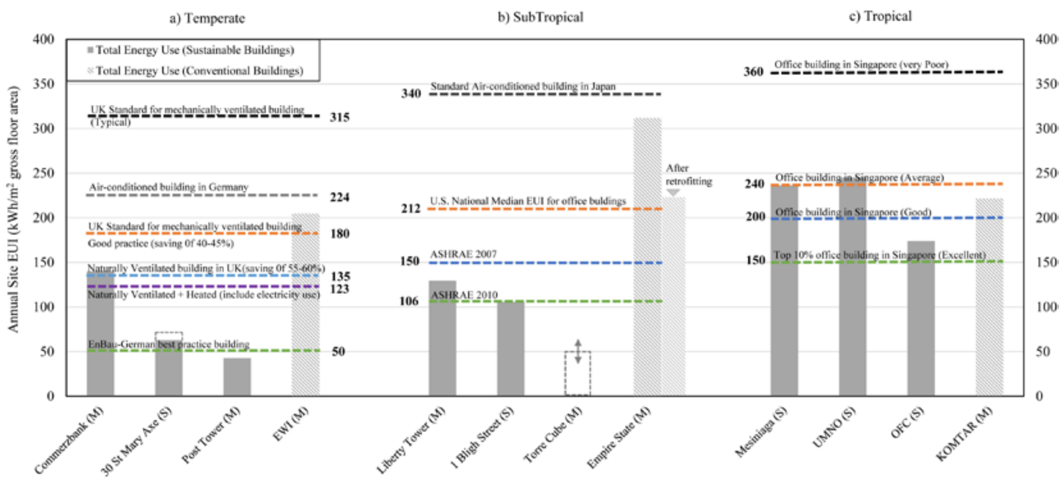


FIGURE 2.8 Comparison of building's energy performance with energy benchmarks in each climate/context. *(S)=Simulated; (M)=Metered; the electricity consumption is the total usage for lighting, pumps and fans. The electricity consumption for lighting pumps and fans has not been published for the Torre Cube. Therefore, the predicted consumption is presented with a dashed line. Energy benchmarks vary with country and source. German benchmarks use net area while UK benchmarks use gross area. In this graph, German energy benchmarks are normalized from net area to gross area with an average space efficiency factor around 65%. The EnBau standard is based on primary energy, therefore the site energy should be even less than the presented figure.*

In the sub-tropical climate, all of the three sustainable cases, have a lower energy consumption than the U.S. National Median of energy use for office buildings and ASHRAE 2007. Moreover, 1 Bligh Street and Torre Cube outperform ASHRAE 2010, with an energy consumption lower than 106 kWh/m². Torre Cube has the highest energy-efficiency with no dependence on cooling or heating systems that is to a large extent related to the mild weather conditions and the relatively low height. The Empire State building is an example of a typical high-rise building with high dependence on air-conditioning systems. Before 2009, the total energy use of the Empire State building was 100 kWh/m² higher than the US building's average energy use (212 kWh/m²). Since 2009, the Empire State building has been retrofitted as such reducing the building's total energy consumption by 38%.

TOC

In the tropical climate, two cases are certified as sustainable, but their energy consumption exceeds the average for office buildings in Singapore. OFC is the only sustainable building that outperforms the energy benchmark for good practice office buildings. Although the KOMTAR building is a typical air-conditioned high-rise building with no sustainable design measures, the energy performance of this building is better than the Mesiniaga and the UMNO Tower. However, it should be considered that the KOMTAR Tower is an outdated building that has some floors unoccupied whereas the other two buildings are fully occupied.

§ 2.8 Discussion of comfort standards

There is no doubt that in some climates, buildings require heating and/or cooling to remain comfortably habitable. The indoor air temperature that is set for a building is a key factor in determining the energy consumption and thermal comfort. Standards, guidelines and legislations for the indoor comfort aim at improving the health and comfort of building occupants while reducing the energy use. ISO 7730 (2005), ASHREA 55 (2010) and European standard EN15251 (2007) are the three widely used international standards which address the indoor environment and thermal comfort (Nicol et al., 2012). Predicting the indoor air temperature at which people feel comfortable is a complex task that depends on several parameters including environmental, cultural and personal factors. The results of field surveys of different buildings and climates showed that the range of the comfort temperature for the people who work in a naturally ventilated building is different in comparison with an air-conditioned one. For this purpose, international standards use different prediction models to specify the comfort temperature boundaries within buildings. The international comfort standards use the predicted mean vote (PMV) index for mechanically conditioned buildings and the adaptive thermal model for naturally conditioned buildings to define acceptable indoor environments. The idea behind the adaptive comfort model is that the occupants of naturally ventilated buildings have a greater degree of control over their environment; therefore, thermal comfort ranges can be extended beyond the normal range.

In naturally ventilated buildings, the occupants' perception of indoor thermal comfort depends largely on outdoor air temperature variations. A comparison of mean monthly outdoor dry-bulb temperature (DBT) with indoor comfort temperature values for buildings in different climates is presented in Figure 2.9. In Figure 2.10, the energy use intensity of case studies along with the number of degree days for heating and

TOC

cooling of each city/climate are provided. Comfort temperatures based on adaptive versus predicted mean vote (PMV) models are obtained from Climate Consultant version 5.4 for different locations. These figures represent 90% acceptability limits of the occupants. The adaptive comfort model and the PMV model are both defined in ASHRAE standard 55. The optimal temperature for comfort (T_{comf}) and the range of acceptable comfort temperatures (T_{accept}) based on the adaptive model are obtained by the following equations.

$$T_{comf} = 0.31T_o + 17.8\ °C$$

$$T_{accept} = T_{comf} \pm T_{lim}$$

In 2004, ASHRAE Standard 55 defined T_o initially as the mean monthly outdoor air temperature and later in the revised version of 2010 as the prevailing mean outdoor air temperature. Therefore, different forms of running mean temperature existed and the exact choice of the adequate form is left to the user according to the latest version of the standard (Nicol et al., 2012). Since the comfort temperatures in this paper are obtained by Climate Consultant version 5.4 and this version of software is programmed according to the ASHRAE Standard 55-2004, T_o represent here the mean monthly outdoor temperature. T_{lim} is defined as the range of acceptable temperatures. When a higher standard of thermal comfort is desired (90% of the occupants being satisfies), the given limits of acceptable comfort temperature is ±2.5K. This equation cannot be used when T_o is less than 10 °C or greater than 33.5 °C. Furthermore, this model does not apply when a mechanical cooling system is available or a heating system is in operation. However mechanical ventilation with unconditioned air may be utilised; thought the thermal comfort should be mainly provided by natural ventilation through operable windows. In Figure 2.9, the adaptive model presented minimum and maximum comfort temperatures for different locations. The lowest value is based on the coldest month that still has a mean monthly outdoor air temperature above 10 °C and that the highest value is based on the warmest month that still has a mean monthly outdoor air temperature below 33.5 °C.

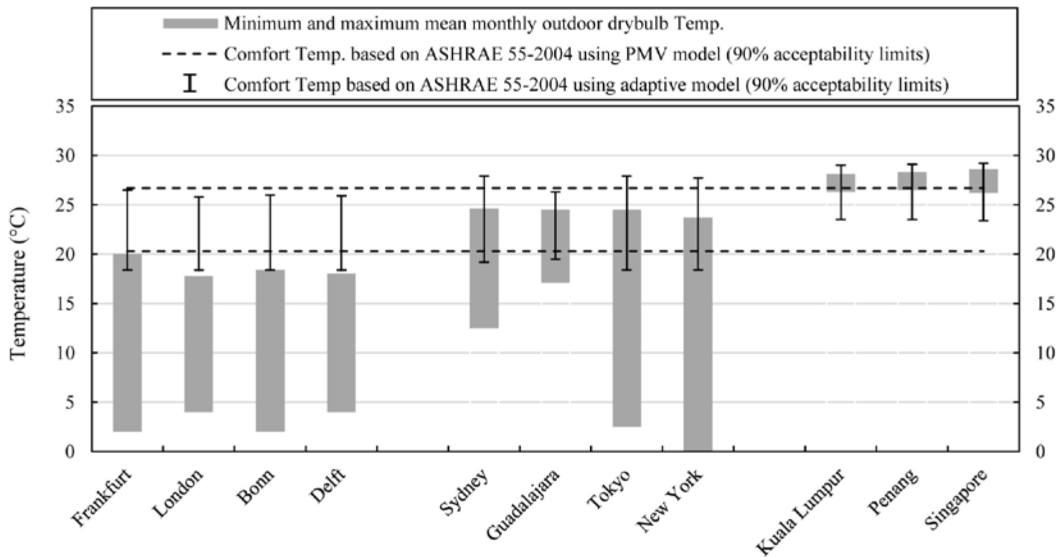


FIGURE 2.9 A comparison of mean monthly outdoor air temperature with comfort temperatures based on adaptive versus PMV models, respectively for buildings with natural ventilation and air-conditioning systems.

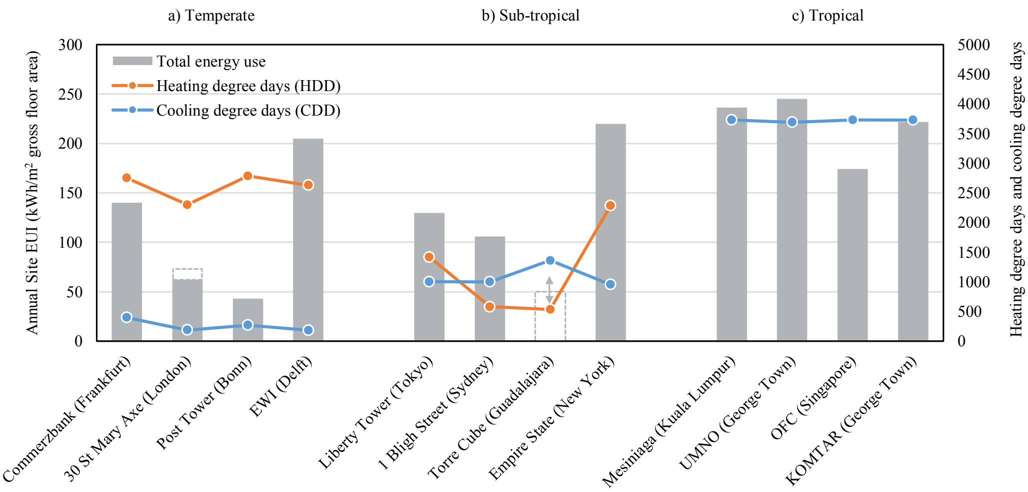


FIGURE 2.10 The energy use intensity of case studies along with heating degree days (HDD) and cooling degree days (CDD) of each city for the same year the energy data were collected.

In a temperate climate, minimum mean monthly temperature for all cases is far beyond the comfort bandwidths, which means heating is the main requirement in this climate. During the summer months, the maximum mean monthly temperature is almost in the same level as the lower limit of comfort temperature. The result of a post occupancy evaluation for Commerzbank (Frankfurt) showed that natural ventilation is possible up to 80% of the year for office spaces. This is a good example of how architectural design elements such as an atrium, sky gardens and a DSF with operable windows can extend the use of natural ventilation. Furthermore, occupants can override the BMS to provide their individual comfort in cellular offices. If occupants decide to open the window, the BMS will automatically switch off the air-conditioning system.

According to the Köppen-Geiger climate classification system (Peel et al., 2007), Sydney, Guadalajara, Tokyo and New York are all classified in the same climate category of sub-tropical. This climate type covers a broad range of features, especially in terms of winter temperatures. However, the solar radiation intensity and the summer temperature are relatively equal for all of the four cases in the sub-tropical climate. The higher energy consumption for heating in the Liberty tower (Tokyo) and the Empire State (New York) is partly explained because of a lower outdoor air temperature in winter compared to Sydney and Guadalajara. Furthermore, as it can be seen in the case of Guadalajara, more than 70% of the year the outdoor air temperature is within the comfort zone, which makes it easier to provide indoor thermal comfort by natural ventilation with no dependence on air-conditioning.

The adaptive thermal comfort model for the tropical climate shows that all cases are within the comfort zone if adequately being naturally ventilated. For naturally ventilated buildings, the availability of control over the indoor environment by the occupants, the cooling effects due to the elevated indoor air velocities and dehumidification of fresh air are some of the factors that can influence the occupants' thermal perception in tropical climates. However, it is important to mention that the solar heat gains and internal heat production can increase the indoor air temperature significantly as a result of which natural ventilation might not be enough and active cooling is required. According to the PMV model, people who are working in air-conditioned spaces would have higher expectations for indoor comfort; hence, have lower tolerance of temperature variations.

§ 2.9 Conclusion

Design strategies for tall office buildings were investigated through a comparative study of twelve high-rises in a temperate, a sub-tropical and a tropical climate. In temperate and sub-tropical climates, sustainable design strategies for high-rise buildings lead to lower energy consumption for cooling, heating, ventilation and lighting. In tropical climates, while some strategies might help to improve user's satisfaction, they can increase the energy consumption if not placed correctly. This means that sometimes a compact building may perform better than a 'perforated' one. Additionally, this research showed which design strategies are most effective for sustainable high-rises to reduce the energy consumption for cooling, heating, ventilation and lighting in three climates.

A mixed-mode ventilation strategy can effectively reduce the energy consumption for cooling also fans in temperate and sub-tropical climates. The effectiveness of natural ventilation can be improved by using special design elements like atrium (central or peripheral) and indoor sky garden, which can also bring daylight deeper into the plan. A fully glazed double-skin façade with automated blinds, operable windows and ventilated cavity is a common façade type among sustainable cases in temperate climate. In climates with higher solar radiation intensity, shading the envelope (e.g. green balconies and sky gardens), placing service areas as a thermal buffer on the hot sides with limited openings and finally minimizing surface to volume ratio are some of the strategies to control the heat gain; hence reducing the cooling demand. Moreover, placing the service core along the façade provide this possibility to be naturally ventilated and lit. Furthermore, the results showed that for tropics there is a need for higher concerns over the design of high-rise buildings since the energy consumption for sustainable buildings is relatively high in comparison with the energy benchmarks for a good practice building.

Acknowledgments

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Appendix 1

Climate data and locations of the selected case studies.

	Average daytime temperature during the hottest months (°C)	Average daytime temperature during the coldest months (°C)	Mean annual temperature (°C)	Average wind speed (m/s)	Global Horiz radiation in summer (Wh/m²)	Global Horiz radiation in winter (Wh/m²)	Average annual RH in summer	Average annual RH in winter
Frankfurt (Commerzbank)	24	4	10	4	4920	626.6	53%	76%
London (Mary Axe)				3.6	4945	742	66%	81%
Bonn (Post Tower)	17.4	3	9.6	3.1	4679	713	72%	83%
Delft (EWI)			10	5.4	4642	821	79%	88%
Sydney (1 Bligh Street)	26	17	18	3.8	6319	2465	66%	62%
Guadalajara (Torre Cube)					5654	3885	52%	60%
Tokyo (Liberty Tower)	29	11	16.1	1.9	4448	2586	72%	50%
New York (Empire State)					5258	1439	69%	63%
Kuala Lumpur (Mesiniaga)	32	31	28	1	4522	4069	80%	83%
Penang (UMNO) (KOMTAR)			27	1.3	5362	4399	81%	82%
Singapore (OFC)	32	29.5	27.5	1.6	4921	4296	85%	82%

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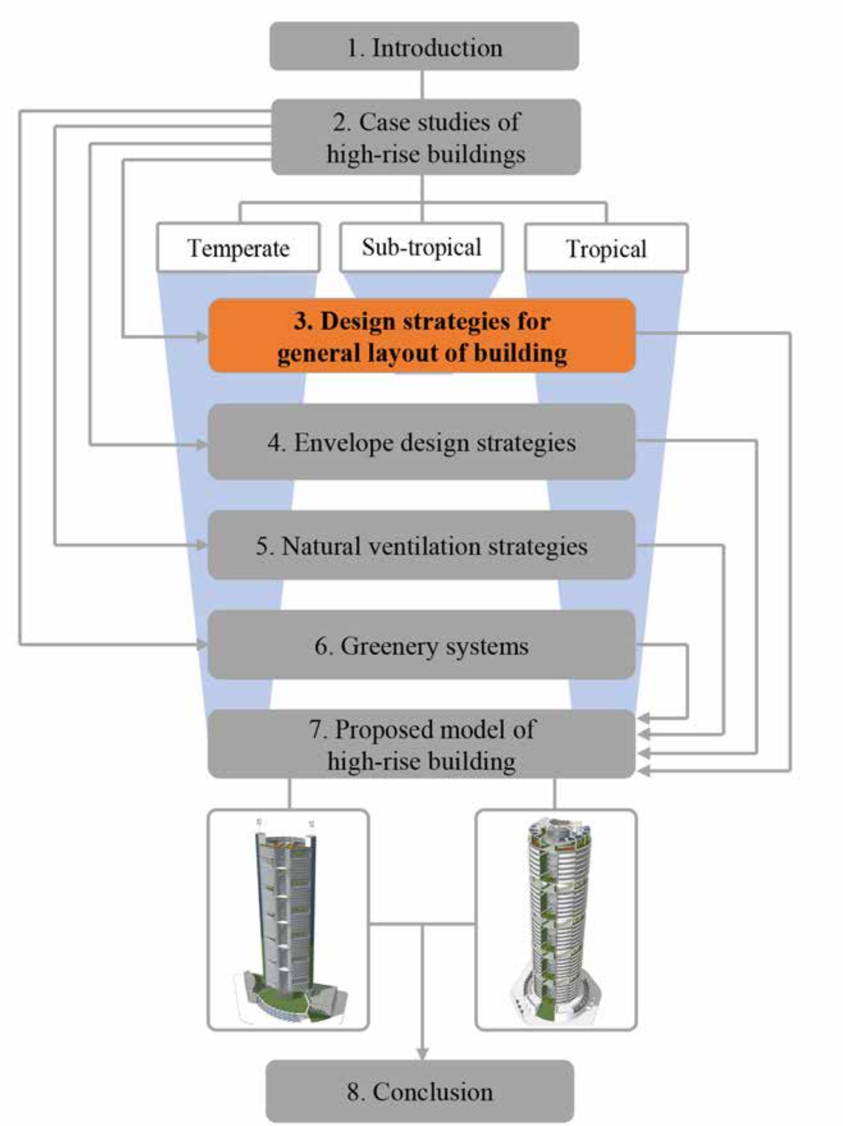
1. Introduction
2. Case studies of high-rise buildings
Temperate
Sub-tropical
Tropical
3. Design strategies for general layout of building
4. Envelope design strategies
5. Natural ventilation strategies
6. Greenery systems
7. Proposed model of high-rise building
8. Conclusion